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THE

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THE FOYAITE-IJOLITE SERIES OF MAGNET COVE: A CHEMICAL STUDY IN DIFFERENTIATION. II.[1]

DISCUSSION.

In the table below are given the chief molecular ratios of those analyses of the Magnet Cove rocks which I am led to believe are the most reliable and representative. There are also

	I	II	III	IV	V	VI	VII	VIII
SiO_2	38.39	38.93	41.75	44.40	49.70	53.09	60.13	60.20
TiO_2	4.54	1.62	0.58	1.53	1.33	0.11	1.15	0.14
Al_2O_3	7.05	15.41	17.04	19.95	18.45	21.16	20.03	20.40
(FeO)	14.33	8.83	9.04	7.41	7.37	3.74	3.45	3.44
MgO	11.58	5.57	4.71	1.75	2.32	0.32	0.76	1.04
CaO	19.01	16.49	14.57	8.49	7.91	3.30	0.87	2.00
Na_2O	0.74	5.27	6.17	6.50	5.33	6.86	6.30	6.30
K_2O	0.75	1.78	3.98	8.14	4.95	8.42	5.97	6.07
MOLECULAR RATIO								
SiO_2	.640	.649	.696	.740	.828	.885	1.002	1.003
TiO_2	.055	.019	.007	.0.18	.015	.001	.014	.002
Al_2O_3	.069	.151	.167	.196	.181	.207	.196	.200
(FeO)	.199	.123	.127	.082	.102	.052	.048	.048
MgO	.290	.139	.118	.044	.058	.008	.019	.026
CaO	.339	.294	.260	.152	.141	.059	.015	.036
Na_2O	.012	.085	.098	.105	.086	.117	.100	.102
K_2O	.008	.019	.042	.087	.053	.090	.061	.065
$\frac{Na_2O}{K_2O}$	1.50	5.00	2.33	1.21	1.62	1.30	1.64	1.57
Specific Gravity	3.407	2.769	3.084	2.770		2.599	2.557	2.642

I. Jacupirangite.
II. Biotite Ijolite.
III. Ijolite.
VI. Arkite.
V. Covite.
VI. Foyaite, Diamond Jo.
VII. Pulaskite, Braddock's quarry.
VIII. Pulaskite, Type, Fourche Mt.

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[1] Continued from p. 622.

inserted the figures for my two analyses of the Fourche Mountain rocks, which, although somewhat distant from Magnet Cove, undoubtedly belong to the same general regional magma. To render the diagrams less complicated the iron oxides are calculated together as (FeO).

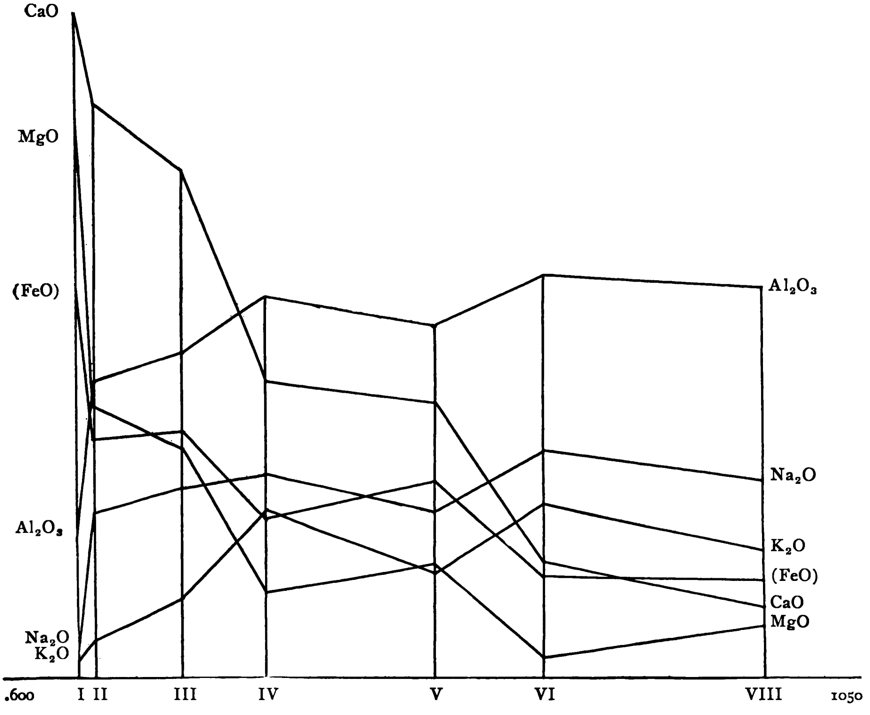

DIAGRAM 1.

It has already been explained that at Magnet Cove the arrangement of rocks from center to periphery is regularly serial, from basic to intermediate, *i. e.*, from II to VI. If, therefore, the analyses are plotted according to Iddings's method, using the silica values for the abscissae, the diagram will represent in a general way the variation of this particular magma in space. This was done in my former paper[1] for the earlier analyses, and the results of the present investigation are shown in Diagram 1.

[1] H. S. WASHINGTON, *op. cit.*, p. 404.

Comparison of the two shows that the curves, or rather zigzags, are much alike even though the analyses of (and consequently the abscissal positions of the figures for) arkite are different in the two. At the same time the new diagram is markedly more broken, and varies less regularly and continuously than the former. The regularly serial character of the first is thus apparently diminished, and what it was thought would be an excellent example of regular differentiation seems to turn out rather the contrary.

But, as Pirsson justly remarks, the use of SiO_2 for the abscissae is arbitrary, and, since this is one of the most important rock ingredients, its variation should also be shown in a manner directly comparable with those of the other oxides.

It would seem to be undeniable that this is a legitimate, indeed a most logical, method if the differentiated mass has not suffered disturbance and if circumstances permit the determination of the correct distances of the various differentiates from the center, since the diagram then represents, not only the compositions of the various phases, but their actual relations in space, both as to direction and as to relative position.

It often happens, as apparently at Magnet Cove, that the successive differentiation products are sharply separated from each other, transition forms being either lacking or very small in amount as compared with the main types. To correspond then with the actual state of affairs, the diagram should consist of steps, *i. e.*, horizontal lines of a length equal to the breadth of each zone, at the respective ordinal positions for each oxide.

Since, however, the analyses may be assumed to represent the average composition of each differentiation product, and we desire to study the course and the laws of differentiation, it is legitimate to represent the position of each constituent by a point, and the lines connecting these will therefore express the course of the differentiation of the mass of magma, even though, as an actual matter of fact, all the possible gradations represented by the curves may not be present. Such a procedure is quite in accordance with the general practice in chemical and physical research, and this point is mentioned only because such methods have, as yet, found little application in petrography.

In order to construct the curves two important field data are required; the position of the center of the mass or area, and the relative distances from this of the various types analyzed.

By center is meant that of the innermost petrographic zone or core, not necessarily the geometrical center of the mass, as this petrographic center may be conceivably geometrically eccentric. Since, in many cases, as here, we have only one section, a horizontal one, this point is not necessarily the center of the mass, but rather its epicenter, to use the seismological term.

Since the area of Magnet Cove forms a fairly regular ellipse with axes of about 5 and 3 kilometers, the center of the igneous area is easily determined. Its position is marked approximately by the Baptist church,[1] which lies in the small central exposure of biotite-ijolite. Inasmuch as we do not know whether the plane of the present exposed area cuts the mass centrally or above the center, we cannot tell whether the central point of this is the true center of differentiation or not. It is probably not so. But as far as the types exposed are concerned this is of little moment, as their mutual relations would remain the same, or approximately so, in any case.

Having determined the center the next point is to determine the distances of the various types from this. It is obvious that for the proper plotting of the curves, and hence the study of the course of differentiation, this is of great importance, since the points which determine the various curves will be shifted in one direction or another according to the distances selected. This would alter very materially the slope of the curves, and even their character or shape, as by the shifting of the abscissal positions a straight line will become a curve, or a simple curve of the second degree may assume the form of an inflexed one of the third.

At Magnet Cove we cannot determine the abscissal positions by simply measuring the distances from the center to the particular spots where the analyzed specimens were collected, because, owing to the elliptical shape of the area, a specimen (*e. g.*, covite) from near the end of the major axis may be at an actually greater distance from the center than one (*e.g.*, foyaite) from the end of the minor axis, though genetically inside the latter.

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[1] *Cf.* the maps in papers already cited.

It would, of course be best to have several analyses of each type from different parts of the zones, both radially and circularly, so as to get the mean composition of each. But as that involves the making of very many analyses, we must be content at present with selecting what seem to be representative specimens, and assume that their analyses correspond to the average composition of each type.

Assuming this, two courses are open to us. We can either measure the distances from the center along a radial line on which all occur, or average the distances of the various occurrences of each type. The latter has been the process adopted here, since it seemed more likely to eliminate errors due to local conditions.

For each type measurements were made on Williams's map in many directions from the Baptist church to the middle point of each zone exposed, and the mean of these taken in each case. On the diagrams the abscissal positions of III, IV, V and VI, from the origin at II represent these relatively, as it is not necessary that the diagrams be of the same scale as the map. The position of the foyaite (VI) is not fixed as accurately as those of the others, since, being at the periphery, it is in great part overlaid by the surrounding shales. Small outcrops outside the main area, however, allow a rough estimate of its average distance, though it undoubtedly extends farther away from the exposed area than the few outcrops indicate.

In my former paper I assumed that the petrographic center of the area was in the "magnetite bed," and that this was the result of the decomposition of underlying jacupirangite. As, however, this is quite uncertain, it seems best for the purpose in view to disregard this area. For the present then the analysis (and the diagram position) of the jacupirangite may be neglected. The same is true of the pulaskite analyses, these rocks lying quite outside the Magnet Cove area. All these rocks will be discussed subsequently.

We thus obtain the result shown in Diagram 2, where the points are connected by straight lines. In this, and the following, the vertical scale for SiO_2 begins .400 lower than the others, so as to condense the diagram and at the same time preserve the relative forms of all the curves (given later), and not flatten that of silica, as would be done if a smaller vertical scale were used for this than for the other constituents.

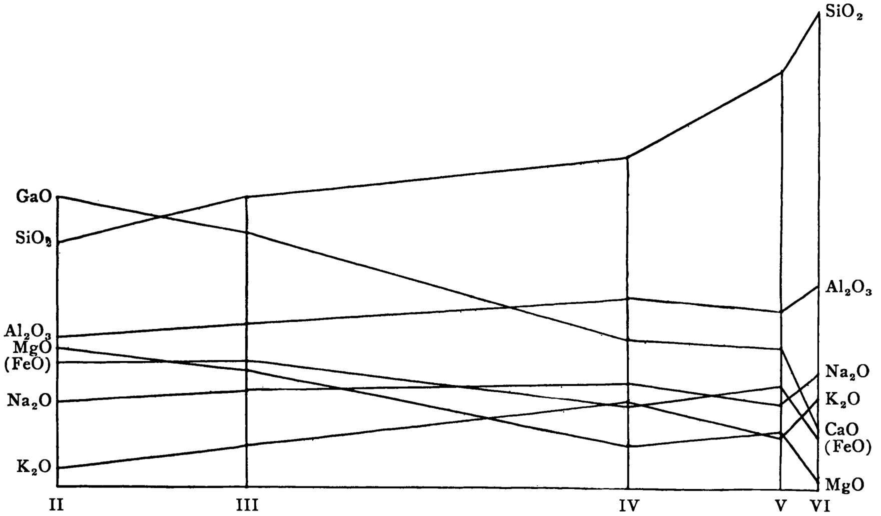

DIAGRAM 2.

When Diagram 2 is examined it is clear that, with the exception of the values for covite (V), all the points of the respective oxides lie along very smooth curves. For convenience in further discussion the curves formed by the figures for II, III, IV and VI are plotted separately in Diagram 3. The values for V (covite) are entirely omitted from this, and the position and relationships of this rock will be discussed later on. The curves marked *F* and *M* will also be explained presently. All the curves, it may be mentioned, were drawn with a spline, so that the personal equation is eliminated as far as possible.

Within the limits from II to VI the curves are simple, that of SiO_2 alone showing inflexion about at the center of the diagram, rising sharply toward the right (acid end) and falling gently toward the left (basic end). Most of the curves are quite flat, especially those of Al_2O_3, Na_2O and K_2O, which approximate straight lines. At the same time they are all distinctly curves and not strictly linear.[1] It will be remembered that Pirsson[2] says that all of the lines of his diagram should probably be drawn as very flat curves (much flatter than these), and these observations are in accordance with the conclusion of Harker,[3] that strictly linear series of rocks are of rare occurrence.

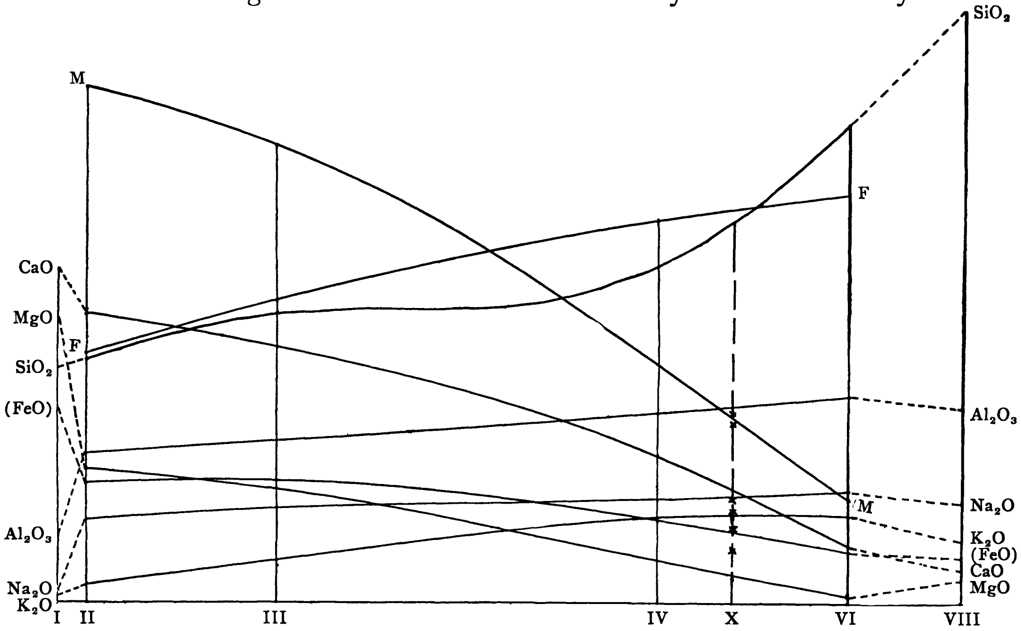

DIAGRAM 3.

With the exception of SiO_2, which is inflexed and that of

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[1] This is best seen in the large-scale drawing from which the diagram is reproduced.

[2] L. V. PIRSSON, *op. cit.*, p. 571.

[3] A. HARKER, JOUR. GEOL., Vol. VIII, p. 392, 1900.

Al_2O_3, which is almost a straight line but slightly convex,[1] all the curves are concave[1] (toward the bottom).

The curves divide themselves naturally into two groups, according to general direction. Those of SiO_2, Al_2O_3, Na_2O and K_2O ascend toward the right (the periphery), the three last almost arithmetically. It will be noticed that the K_2O curve ascends more rapidly than that of Na_2O to a point a little to the right of IV, when it drops a trifle more rapidly. This is expressed in the series of the ratios of these two oxides, already given in Table I. The second group is that of (FeO), MgO and CaO, which descend toward the right, and at a greater rate than those of the other group rise, SiO_2 excepted.

It may be noted, by the way, that if TiO_2 be plotted with SiO_2, the curve of the sums of the two becomes rather more flat (especially about IV), and the inflexion at the left is almost overcome. For facilitating this observation I have put the molecular ratios of TiO_2 next to those of SiO_2 in the table, though it would complicate the diagram unnecessarily to put in this joint curve. This seems to confirm the general belief that TiO_2 plays the part of an acid radical, like SiO_2, in rock magmas.

The general results can be concisely shown by plotting the sums respectively of the "ascending" and the "descending" oxides, except silica. We then get the two curves *F* (that of Al_2O_3, Na_2O, K_2O) and *M* (FeO, MgO, CaO), on the line of which all the determining points fall very exactly. They are both decidedly concave, *F* ascending and *M* descending, and their smoothness and regularity are very striking.

These results are in strong harmony with those of Pirsson, and the general characters of the curves in each diagram are very similar, though there are some differences in detail. Thus all his curves are much flatter, the SiO_2 does not show signs of inflexion, and the Al_2O_3 is concave and K_2O convex, while in mine these two are reversed. But these are small matters, possibly due to the abscissal distances at Yogo Peak not being as easily ascertainable as at Magnet Cove. The general conformity of the two is very good evidence to show that, if plotted according to their spacial (*i. e.*, genetic) relations in the mass, the analysis of the components of an igneous complex will furnish regular curve. This fact is almost proof positive of the view that the variation of rocks is due to differentiation of some sort.

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[1] The terms convex and concave will be understood as referring always to the *X* axis, the bottom of the diagram.

Whether this differentiation is always as is now believed, viz., that the oxides of Al, Na and K tend to segregate in one direction, while those of Fe, Mg and Ca segregate in another, as well as the process by which these changes are brought about, are separate questions, which further investigation must settle. It may be that the general course indicated by the diagrams of Pirsson and myself are typical of all rock differentiation, or it may be that with magmas of different character the course of differentiation may be radically different, and that the same oxides do not always tend to go together.

At any rate, it may be confidently expected that where a mass of magma has been differentiated *in situ* and is of approximately regular shape, has not been subjected to secondary disturbing conditions, and the exposures sufficient, we can express the relations of the differentiation products and the course of differentiation mathematically, as has been done in these two instances. Of course, for this purpose, it is absolutely essential that the analyzed specimens be representative, and that the analyses be complete and accurate. Otherwise the curves will be misleading or else uneven zig-zags, only rough approximations to the truth, and possibly not even that. There must also be present at least three differentiates, as otherwise only straight lines connecting the two can be drawn.

The fact that the SiO_2 curve is the only one which is inflexed, and that it runs very sharply up toward the acid end, leads to some interesting conclusions. Since, toward the acid end, the curves of (FeO), MgO and CaO drop much more rapidly than those of Al_2O_3, Na_2O and K_2O, it is evident that at a short distance to the right (in other words with a slight increase in silica), they will practically disappear if the differentiation continues as indicated by the body of the diagram. Further differentiation in this direction then would lead to the production of a purely feldspathic or feldspathoidal rock. If continued still further quartz (free silica) would appear and the rock become aplitic in character. Finally, since the silica is increasing at a rapid geometrical rate, while the other constituents are dropping, the extreme result of differentiation in this direction would be pure quartz.

This inference is obviously in line with the experiments of Barus and Iddings[1] which indicated that in igneous magmas SiO_2 plays the rôle of electrolytic solvent, analogous to that of H_2O in aqueous solutions. This result is also in harmony with the experiments and conclusions of Lagorio[2] and Morozewicz,[3] who come to the conclusion that the predominant magmatic solvent is composed of silica and alkalis, and that it has the power of dissolving large amounts of alumina. The results obtained above would indicate that alumina itself is an essential constituent of the solvent, and it would also seem that there need be no stoichiometrical ratio between the four constituents. As has been indicated above, however, it will not do to push conclusions too far from such meager data, and it is by no means necessary to infer that a rock solvent of this character is the only possible one. But it will be as well to defer all discussion of these topics until more complete data are available.

The comparative rarity of occurrences of purely or very highly siliceous igneous rocks may presumably be ascribed to the fact that long before this phase of differentiation has been reached, the mass will, in most cases, have become solid (owing to the high melting point and great viscosity of such mixtures), and hence incapable of further change in this way.

It is of interest to note in this connection that a specimen of "aplite" has been collected by Dr. Weed, and is now in the

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[1] BARUS and IDDINGS, *Am. Jour. Sci.*, Vol. XLIV, p. 248, 1892.

[2] LAGORIO, *Min. Pet. Mitth.*, Vol. VIII, p. 508, 1887.

[3] MOROZEWICZ, *Min. Pet. Mitth.*, Vol. XVIII, p. 235, 1899.

United States Geological Survey Reference Collection (No. 813). It is of a small dike, about one and a quarter inches wide, cutting the shale near Neusch's gulley, which it has metamorphosed. I am indebted to Dr. Ransome for the examination and description of this specimen which he sent at my request. "Under the microscope, the dikelet is seen to consist almost wholly of cloudy alkali-feldspar, with no quartz or nephelite, and a little biotite. With high power, the feldspar (between crossed nicols) all shows the fine shadowy striping indicative of a soda-bearing feldspar." Two garnets also occur at the borders of the dike. The occurrence of this aplite dike is clearly corroborative of the view of the course of differentiation which has been just expressed, and it is probable that further search would reveal others which have heretofore escaped notice.

Turning to the other end of the diagram, there is good ground for the belief that there must be inflexion upwards of one or more of the curves beyond II to the left. If the curves are extrapolated to the left, at a distance, let us say, equal to that between II and III, the sum of the constituents reduced to precentages amounts to only 55.6.

It is obvious therefore, either that some other component of the magma than any of those plotted is greatly concentrated at the basic end, or else that the curves of one or more of the plotted constituents must run very sharply upward, thus causing inflexion.

In the former case a probable additional constituent would be P_2O_5, which would yield, with high CaO, MgO and (FeO), an apatite-rich pyroxenite like that of Ahvenvaara in Finland,[1] or with disappearance of SiO_2, an apatite-magnetite rock like that of Alnö.[2] If TiO_2 should be the constituent to assume extraordinary proportions toward the basic end, we would expect, with disappearance of SiO_2, titaniferous magnetites, or such rocks as the magnetite-perofskite rock of Brazil, described by Derby.[3]

[1] V. HACKMAN, *Bull. Com. Géol. Finl.*, No. XI, p. 36, 1900.

[2] *Cf.* ROSENBUSCH, *Elemente*, No. 3, p. 133, 1898.

[3] O. A. DERBY, *Neues Jahrb.*, 1894, Vol. II, p. 297.

Such products are, however, very exceptional, and are only to be expected in cases of very complete differentiation. In general we would only look for sharp upward inflexions of the (FeO) and MgO curves, which would yield, with the slowly dropping silica and the high CaO, a pyroxenite rich in magnetite. This is just the character of the jacupirangite of Magnet Cove (I), and of those of Brazil and Alnö, and I have indicated its connection with the others accordingly by the dotted lines to the left.

Inasmuch as the specimens of this come from a small isolated mass outside the main area, its relations to the other types are uncertain, and its diagrammatic position has been given on the basis of its silica content. It seems to be probable that if, as is likely, such a rock is connected genetically with the others, its abscissal position should be considerably more to the left. As this rock is met with in the immediate vicinity of the main area, and is a theoretically possible differentiation product of the magma, it seems reasonable to assume that the section at Magnet Cove cuts the mass some distance above the center, and that below the biotite-ijolite is a core of jacupirangite, as previously supposed.

It is obvious from the theoretical discussion, as well as from observations here and at similar regions, that the relations toward the basic end are far more complex than at the acid end. This arises from the fact that the oxides involved here are capable of more numerous mineralogical combinations, and also because elements which are only present to a small extent in the body of the magma may here assume proportions of great importance. The fact that these extreme basic differentiation products are far more common than the purely siliceous ones may be ascribed to the greater fusibility of magmas of a basic character, and the consequent possibility of differentiation among them at temperatures when the more acid end of the series is solid.

In this connection attention may be called to the fact, analogous to the segregation of TiO_2 and P_2O_5 at Magnet Cove and Brazil, that in large steel castings, such as those for modern artillery, etc., there is a very marked concentration of "impurities," as phosphorus and sulphur, toward the center of the mass.

As all the curves are so smooth and well defined, it seems highly probable that equations for them could be found and that their properties as such could be discussed. In this way we could get at an exact knowledge of the law of differentiation, in this particular case at least. It is a matter of regret that I am not mathematician enough to do this, but there are other applications of the data at hand which are capable of simple mathematical treatment.

Since the area of Magnet Cove is a fairly regular ellipse, and the zones of the various types are concentric about the center, by taking the average distance of each we practically reduce the ellipses to circles, the average distances being the radii.

Now, since II is at the center, if we suppose Diagram 3 to be revolved about the vertical line at II as an axis, it follows that the solids of revolution so generated by each of the curves (with the bounding lines at the sides and bottom), will represent the amount of each oxide in the original magma, and that their sum will represent the composition of the magma as a whole, before differentiation.

This is not strictly true, since we are ignorant of the exact shape and extent of the complex, but as a first approximation and an illustration of the method, it will be of interest to calculate the results which are obtained on this basis. As a matter of fact, the recent description of the Shonkin Sag laccolith by Weed and Pirsson[1] renders it extremely probable that the foyaite is present in far greater relative amount than the surface exposures indicate. This would necessitate a very considerable correction, but, as we have no means at present of estimating this, it will be as well to give the figures based solely on the field observations, leaving possible corrections for the future.

The process of calculating the various volumes is very simple in theory, but somewhat complicated and laborious in practice.

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[1] WEED and PIRSSON, *Am. Jour. Sci.*, Vol. XII, p. 1, 1901.

As it is a somewhat new departure in petrography it may be of use to others to outline the method which I have employed. The curves shown in Diagram 3 were plotted on paper ruled in inches and tenths. The particular scale is simply a matter of convenience, and it is not necessary to reduce the percentages to 100, as we are dealing with relative amounts.

The formula employed is well known, being the second of Guldin's theorems, viz., the volume of the solid generated by the revolution of a closed curve or plane figure about an axis in its plane, but exterior to itself, is equal to the product of the area of the generating curve into the path described by the center of gravity of the revolving area.

$$V = 2\pi r A,$$

where V is the volume, r the distance from the axis to the center of gravity, and A the area of the plane figure.

The areas of the curve, *i. e.*, of the space embraced within the curve itself, and the limits of the diagram, are easily found, either by counting the squares, or by calculation of the area of the trapezoids formed by the respective chords and the limiting lines, and addition to these of the areas embraced between the chords and the curves.

The centers of gravity are found by dividing the trapezoids into two triangles, and finding their centers of gravity, when the center of gravity of the trapezoid will be at the intersection of the line connecting the centers of the two triangles and one connecting the middle points of the two parallel sides. In the case of the more curved lines a correction must be made for the area between the chord and the curve, but this will always be small. SiO_2 was regarded as composed of the large rectangle from .400 below the bottom of the diagram to .249, and the space between this upper boundary and the inflexed curve.

The resultant volumes, being based on the molecular ratios, have to be multiplied by the molecular weights of the respective oxides, in order to arrive at the percentage composition of the whole. In this way I obtained the following figures, which are given in full to illustrate the method.

	A	r	V	V × mol. wt.	Percentage	MOL. RATIO	
						Found.	Calc.
SiO_2	52.0 6.0	4. 5.4	1306.2 203.4	90576.0	47.24	.787	.787
Al_2O_3	14.0	4.25	375.7	38321.4	19.99	.196	.201
(FeO)	8.25	3.5	181.0	13032.0	6.80	.094	.074
MgO	5.9	2.9	107.4	4296.0	2.24	.056	.029
CaO	16.2	3.5	356.1	19941.6	10.40	.185	.117
Na_2O	8.1	4.1	208.6	12933.2	6.75	.109	.110
K_2O	8.8	4.75	134.2	12614.8	6.58	.070	.090
					100.00		

Of the Magnet Cove rocks this resembles most that of arkite (IV), especially as regards Al_2O_3, (FeO), MgO, and Na_2O, though it is distinctly higher in SiO_2 and CaO and lower in K_2O. Referring it to Diagram 3, its position established by means of SiO_2 is shown at *X*, and the points where this vertical is cut by the oxide curves are the "molecular ratios calc." of the table. The small crosses along the vertical indicate the positions of the various oxides as found. They can be identified by the values in the table.

It will be observed by reference to the diagram or to the last two columns of the table, that in the case of oxides whose curves are approximately straight lines, as Al_2O_3 and Na_2O, the found and calculated values coincide, while in the case of oxides yielding decided curves the value found is below that calculated.

This is in accordance with the demonstration of Harker[1] that if a series be linear the admixture of two or more members will produce a rock having the composition of a possible member of the series, while in a curvilinear series the mixture will not correspond to a possible member.

Another method for arriving at the composition of the magma as a whole would seem to be furnished by the determination of the mean point of each of the curves, thus giving the average composition. If the equations of the various curves were known, these could be calculated mathematically. But for practical purposes it can be done by determining, for each oxide, the ordinal value for each successive tenth of an inch, and taking the mean. The result of this process is given in II below, that given by the previous process being given in I.

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[1] HARKER, JOUR. GEOL., Vol. VIII, p, 394, 1900.

	I	II
SiO_2........	47.24	45.44
Al_2O_3......	19.99	19.06
(FeO).......	6.80	7.75
MgO........	2.24	3.31
CaO........	10.40	11.81
Na_2O.......	6.75	6.37
K_2O........	6.58	6.26
	100.00	100.00

The two agree fairly well, and are of the same general character, though there are marked discrepancies, II being decidedly more basic in all respects than I. What may be the explanation of this, I am not mathematician enough to say. But the general agreement would indicate that one of the two, or their mean, cannot be far from the truth, *i. e.*, as near as the data at hand permit of approximation.

It is of interest to note that I have been unable to find the analysis of any rock which agrees at all closely with either of these two results. Those which are as high in alkalis being lower in bivalent oxides, while those which agree in this respect are lower in alkalis and alumina. Whether this indicates that there are serious sources of error in the method employed, or else that some undifferentiated magmas may possess chemical compositions not corresponding to those of rocks as yet known, is a question which cannot be decided here. It would seem as if there were nothing *a priori* contrary to the latter hypothesis.

In this connection Harker's[1] remark may be cited: "Given a series such that its diagram has markedly curved lines, the result of the admixture of two members may be something not only foreign to the series, but highly peculiar by comparison with igneous rocks in general." It is true that Harker was discussing the case of the mixture of two members of a series, but

[1] HARKER, *op. cit.*, p. 395.

differentiation and admixture (of two members of a series) may to a certain extent be regarded as inverse processes, so that the occurrence of a magma of this anomalous composition need not occasion surprise. Being rich in both of the generally antagonistic groups of oxides, it would be especially liable to differentiation. The general lability of the monzonitic magmas as regards the conditions controlling crystallization has been pointed out elsewhere.[1]

The general chemical composition can also be calculated by the relative volumes of the various phases, which has been the only method heretofore available. This would seem to be far more uncertain than the new method, which is based on the mathematical course of differentiation, since the ignorance of certain data may affect the result very seriously. Thus we cannot tell where the boundaries between two zones really fall, and (beneath the hornstone ridge especially) whether there may not be a zone of transitional material.

Assuming that the limits come half way between zones, and that they are of uniform thickness in all directions, we can easily

	Volumes	Weights
II	0.14	0.15
III	8.64	9.85
IV	38.27	39.15
VI	52.95	50.85
	100.00	100.00

SiO_2	50.02
Al_2O_3	20.89
(FeO)	5.87
MgO	1.36
CaO	6.89
Na_2O	6.86
K_2O	8.10
	100.00

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[1] F. L. RANSOME, *Am. Jour. Sci.*, Vol. V, p. 370, 1898. H. S. WASHINGTON, JOUR. GEOL., Vol. V, p. 376, 1897.

calculate the volumes of the several spherical shells, which must also be assumed to represent the true ellipsoidal ones. The results are given below, including the relative volumes and weights (obtained by correction of the former for specific gravity), and the average composition deduced from this latter.

This result is notably less basic than the former calculated from the curves, and approaches somewhat closely to the compositions of the foyaite and the arkite, though in a general way intermediate between the two. This is so, since these two form (on this basis) 90 per cent. of the whole. It must be remembered, however, that this method is not based on curves, but on a succession of steps, and that the influence of the greater width of the more acid phases is intensified by their greater distance from the center. At the same time both methods indicate a magma rich in Al_2O_3, CaO and alkalis, low in SiO_2 and MgO, and with moderate iron.

Inasmuch as there must be a (probably rather large) correction made for the greater mass of foyaite, on the analogy of the Shonkin Sag laccolith, all these figures can, for the present, be regarded as only suggestive and illustrative of the method of investigation proposed, than representing exactly the actual state of affairs.

It is of course hazardous to theorize on such limited data as are yet available, but the methods indicated in Pirsson's paper and the present one would seem to be of not uncommon applicability, and well worth further trial in the investigation of other favorable localities. Indeed, as Pirsson has remarked,[1] "it would seem as if this should be the point of departure in the study of other series." The methods indicated certainly put the study of rock differentiation upon a purely mathematical basis, which in the hands of a competently mathematical petrographer, should surely lead to an exact quantitative knowledge of the laws which control this, and very probably, with the aid of physical chemistry, to a knowledge of the rationale of the process.

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[1] PIRSSON, *op. cit.*, p. 576.

In my former paper I suggested as an explanation of the exceptional character of the Magnet Cove and Umptek laccoliths, in having the borders more acid than the centers, that the arrangement depended on the general chemical character of the undifferentiated magma. The process of differentiation was conceived to be, at least for such small bodies, in great part, a sort of fractional crystallization, the magma being regarded as a solution, so that, in accordance with the laws of cooling solutions, the solvent (*i. e.*, the portion present in excess) crystallizes out first around the borders on cooling of the mass.

From what has been learned of the composition of the magma, it is evident that, even though low in silica, it was originally of a decidedly leucocratic character. In other words, the potential feldspathic and feldspathoidal constituents predominated very largely over the calco-ferromagnesian. This is seen plainly from the relative weights of the spherical shells, but even the more basic composition derived from the curves shows the same thing. Thus the composition with 47.24 per cent. of SiO_2 may be obtained approximately by several different mixtures of all or some of the types analyzed, but in every case it necessitates taking from six-tenths to eight-tenths of foyaite, or foyaite and arkite. It seems scarcely necessary to give these calculations, which are purely empirical. The same composition may also be reduced to mineralogical composition in several ways, according to the assumptions made, but here, also, we get about two-thirds of leucocratic minerals.

The original body of magma, then, at Magnet Cove was, notwithstanding its low silica, decidedly leucocratic, as demanded by the theory, so that the alumina and alkalis, with the proper amount of silica for the formation of feldspar and feldspathoids, playing the rôle of solvent, would crystallize first, and hence form the outer portion of the mass.

The latest paper by Weed and Pirrson, already cited, is of great interest in this connection. Here it is shown conclusively that in the well-dissected Shonkin Sag laccolith the outer melanocratic shonkinite is present in enormously greater quantity than the core of syenite, which, though basic, is distinctly leucocratic. The composition of the whole, then, would be melanocratic, as demanded by the theory, though with notable amounts of alkalis and alumina. The same general relations are assumed by analogy for the previously described Square Butte laccolith, whose magma thus possessed a similar strongly melanocratic character, *i. e.*, with a basic "solvent" portion, as was suggested.[1]

In this connection attention may be called to two other examples of differentiated masses in which the borders are more acid than the center. One is the igneous area at Alnö,[2] which is of special interest, since the rocks of this locality are very much like those of Magnet Cove. Another example is that of the Rieserferner massif in the Tyrol as described by Becke.[3] The central part of this is a typical tonalite, while the borders are composed of what is called "Randgranit." Although, unfortunately, no analyses are given, it is very evident from the descriptions and from the separations by heavy solutions that the border rock is decidedly higher in alkalis (especially potash) and silica than the main central mass.

Another region which offers close analogies in many ways with that under discussion is that of Ice River, in British Columbia, the rocks of which, collected by Dr. G. M. Dawson, have been briefly noticed by A. E. Barlow.[4] As the specimens were collected on a hasty trip, nothing is as yet known of their mutual relations in the area, but they form an unbroken series "from the most basic ijolite containing 36.988 per cent. of silica, to ordinary nepheline and sodalite syenites containing 53.638 per cent. of silica." Through the kindness of Dr. Barlow I have been able to examine sections of the ijolite, and it is interesting to note that, while closely analogous to the ijolites of

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[1] H. S. Washington, *op. cit.*, p. 411.

[2] Högbom, *Afh. Sver. Geol. Unders.*, No. 148, 1895. Map II. This is explained by Högbom as due to melting and absorption of the surrounding gneiss.

[3] F. Becke, *Min. Pet. Mitth.*, Vol. XIII, p. 379, 1893.

[4] A. E. Barlow, *Science*, N. S., Vol. XI, p. 1022, 1900.

Finland and Magnet Cove in most respects, yet that here hornblende replaces augite, thus differing from other known occurrences of this rock. It seems probable that these rocks are not as rich in lime as those of Magnet Cove, but higher in MgO and FeO.

In regard to the possible fourth type of laccolithic differentiation, which was mentioned in my previous paper, namely, that with a gabbroitic or peridotitic or pyroxenitic composition, the suggestion may be advanced here that representatives of this are to be found in the numerous sheets and dikes of diabase, which, as is well known, seldom show marked differentiation between the borders and the center. This is in accord with the view that in these masses the "basic" solvent is present to the almost total exclusion of the feldspathic portion.

As Pirsson has already pointed out,[1] the viscosity of the magma has an important bearing on the form assumed by an intruded mass. The highly viscous acid magmas will tend to arch up the overlying strata and form high laccoliths, while the more fluid, basic magmas do not possess sufficient viscosity to do this in general, and will hence form relatively thin intruded sheets. But, at the same time, many of these sheets are of thickness sufficient to allow of differentiation, if that had been possible through the composition of the magma.

Such sheets, then, may be regarded as the basic homologues of the acid, undifferentiated laccoliths of the Mt. Henry type, differing in form, but like them in that the solvent is largely in excess in the magma, and hence not susceptible to differentiation.

The abnormality of covite has been briefly noted, and a few words must be devoted to it before bringing this paper to a close. It will be observed on reference to Diagram 2 that for this rock the positions of SiO_2, Al_2O_3, Na_2O, and K_2O are below the corresponding abscissal points of the "normal" curves, while those of (FeO), MgO, and CaO are above. In other words, the positions of all the constituents of covite are consistently inversions of what may be called the normal (for Magnet

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[1] L. V. Pirsson, *Eighteenth Ann. Rep. U. S. Geol. Surv.*, Pt. III, p. 586, 1898.

Cove); where the curve actually ascends, these would cause it to descend, and *vice versâ*.

Three explanations may be advanced for this. The first is, assuming that the covite is a primary differentiation product like II, III, IV, and VI, that the course of differentiation was not regular, but subject to comparatively large variations of an irregular character. This seems to be unreasonable *a priori*, and is also rendered untenable by the great regularity of the curves, if this type be left out of account, by the fact that the abnormalities are systematic in direction, and correspond inversely to the general characters of the respective "normal" curves, as well as by the field relations of this rock.

Another explanation is that the covite is a mixed rock, produced by the combination of either two differentiates of the magma, or one of its differentiates with foreign rock. That it cannot have been produced by mixture of arkite and foyaite is clear from the fact that many of its constituents are not intermediate between those of these two. It might have been produced by a mixture of foyaite and either ijolite or biotite-ijolite though its position in the complex militates strongly against this view. That it is not due to a mixture of the magma, or parts of it, with the country rock is evident from the composition of the latter, which is too low in MgO and CaO to form covite from foyaite, and too poor in alkalis to form it from the more basic members. Its position in the mass, between the foyaite and arkite, not on the extreme border, is also adverse.

The last, and most probable, hypothesis is that the covite is not the result of the primary differentiation which produced the other types, but of a secondary differentiation of one of the differentiaties of the primary process. In such a further differentiation we would expect the same oxides to differentiate in directions like those of the primary process, but in an intensified degree. This, in the case of the more basic of the two complementary secondary differentiates, would give rise to just the abnormalities noted in regard to covite.

Of just what particular phase of the primary differentiation this secondary differentiate is a product it is a little difficult to say, but the evidence of Williams's descriptions, my own observations, and the mineralogical and chemical data, indicate that it was the foyaite sub-magna (VI) which has undergone this further change.

If this view be correct there must exist a complementary differentiate, a rock in which the positions of the various oxides are, as regards the "normal" curves, inverse to those of covite. That is, the loci of silica, alumina, and the alkalis would be above, and those of iron oxides, magnesia, and lime would be below, the "normal."

Whether we actually find this rock or not is more or less an accidental matter of erosion, etc. But a chemical analysis indicates that such exists in the case of the "foyaite" which occupies the small area in the northeastern part of the main mass, which was erroneously colored as ijolite on Williams's map.[1] This is a white, coarse-grained, holocrystalline rock,

	I	II	III	IV	Ia
SiO_2	53.54	53.09	49.70	53.11	.892
Al_2O_3	23.95	21.16	18.45	23.62	.234
Fe_2O_3	1.11	1.89	3.39	1.36	.007
FeO	1.24	2.04	4.32	1.47	.017
MgO	0.08	0.32	2.32	0.33	.002
CaO	0.71	3.30	7.91	1.51	.012
Na_2O	8.62	6.86	5.33	8.25	.139
K_2O	8.87	8.42	4.95	8.43	.094
H_2O (110°+)	1.09	1.13	1.09	....	....
H_2O (110°−)	0.14	0.24	0.25	....	....
CO_2	0.20	0.82	none	....	....
TiO_2	trace	0.11	1 33	....	....
P_2O_5	....	0.15	0.40	....	....
Other constituents	....	0.95	....	1.82	....
	99.55	100.48	99.44	100.00	

I. Foyaite, northeast part of area.
II. Foyaite, Diamond Jo quarry.
III. Covite, schoolhouse, western part of area.
IV. Mixture of eight parts of I, and one of III.
Ia. Molecular ratios of I.

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[1] *Cf.* H. S. WASHINGTON, *op. cit.*, p. 394, note.

composed of alkali feldspar, with nephelite (partly altered to cancrinite), and rare grains of aegirine-augite. The position of this, outside the zone of arkite, is where we would look for such a differentiate of the foyaite magma.

The analysis, made by myself, of this rock is shown in I above, those of the primary foyaite and the covite in II and III, the molecular ratios of I being given in Ia, for comparison with those of the others on a preceding page. It will be seen that the values obtained for the main Diamond Jo foyaite, which is quite typical of this rock found around the border, are intermediate in every case between those for the other two rocks. Reference to Diagram 2 will also make evident the fact that the positions of the various oxides would be, as regards the normal curves, exactly the inverse of those of the covite. The figures for the new analysis fall above or below their respective curves, where those of covite are below or above. This is just what would be expected in the case of secondary differentiates, as has been explained above.

The results of a mixture of eight parts of I and one part of III are shown in IV. It approximates fairly well to the composition of the typical foyaite, especially in SiO_2, MgO, and K_2O, though Al_2O_3, and Na_2O are considerably higher, and iron oxides and CaO lower.

It may be of interest to give the calculated mineralogical composition of I, which works out as follows:

Orthoclase - - - -	52.3
Nephelite - - - -	36.9
Cancrinite - - - - -	2.8
Aegirite - - - -	3.2
Diopside - - - - -	3.7
Extra alumina - - -	1.0
	99.9

The possibility of a secondary differentiation taking place in a primary differentiate is, it must be conceded, difficult to reconcile with the hypothesis already advanced, since according to this the differentiation takes place by a successive crystallization, *i. e.*, solidification of the magma, and any such process is, of course, impossible in a solid mass of rock.

This difficulty, however, does not seem to be insuperable. The evolution of heat on the solidification of molten lava is a well-known phenomena, having been actually observed, and the same has been experimentally verified, and the amount of heat evolved on the solidification of diabase has been determined by Barus.[1] Therefore the crystallization of minerals from a molten magma is an exothermic change.

It is therefore conceivable that the solidification of a laccolithic mass may give rise to sufficient heat to remelt portions of it, which might easily remain liquid long enough for a secondary differentiation to take place. That this was actually the case at Magnet Cove cannot be definitely shown, but it is at least an explanation which has a certain degree of probability in its favor.

In regard to problems of interpolation and extrapolation, by which Pirsson obtained such close agreement between calculated and observed chemical composition, we are not in a favorable position, since the analyses which I have made exhaust the known main types of abyssal rocks at the locality. A comparison of the analyses of the dike rocks given by Williams with the curves in Diagram 3 confirms the supposition expressed in my former paper that the tinguaites and the nephelite-porphyry are aschistic, and that the fourchites and ouachitites like the covite, are diaschistic.

It was expected that the analyses of the Fourche Mountain pulaskites would fall in with the curves as laid down. But, determining the abscissal position by silica, it is found that Al_2O_3, Na_2O, and K_2O are below, and (FeO), MgO and CaO are above, what would be their "normal" positions, as will be seen on reference to the diagram.

Although these rocks are unquestionably derived from the same general magma, yet, as their distance from Magnet Cove is about forty miles, it is clear that we need not be surprised to find discrepancies, due to differences in the process of differentiation.

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[1] C. BARUS, *Am. Jour. Sci.*, Vol. XLIII, p. 56, 1892.

At Magnet Cove we have, without any doubt, the results of the differentiation in place of a small body of magma. This particular mass may have had originally the composition of the magma underlying the whole region, or it may have been itself a differentiate of this. Differentiation in such a large body of magma as that underlying the whole igneous region of Arkansas would naturally be likely to give rise to diverse products at different points, in which, however, could still be traced some of the original general characters of the whole. We are as yet scarcely in the position to deal with such intricate and obscure problems, but the results of Pirsson's investigations and of those embodied in the preceding pages seem to furnish a promising means of attack.

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